MRAM ARRAY EMPLOYING SPIN-FILTERING ELEMENT
CONNECTED BY SPIN-HOLD ELEMENT TO MRAM CELL STRUCTURE
FOR ENHANCED MAGNETORESISTANCE

BACKGROUND

5 [0001] This invention relates to magnetoresistive thin films and to devices having magnetoresistive elements for magnetic data storage, particularly in magnetic random access memory arrays.

[0002] Sun et al. U.S. Patent No. 5,792,569 describes a tri-layer thin film magnetoresistive device having doped perovskite manganate thin films as ferromagnetic elements, separated

10 by a barrier layer.

[0003] Parkin U.S. Patent No. 5,801,984 describes a magnetic tunnel junction device, including a high coercivity fixed ferromagnetic multilayer structure and a single free ferromagnetic layer, separated by an insulating tunnel barrier layer. The fixed ferromagnetic multilayer is made up of two layers, a first ferromagnetic layer with a coercivity substantially

15 higher than the applied field, and a thin ferromagnetic interface layer located between and in contact with the insulating tunnel barrier layer. The material of the first ferromagnetic layer of the multilayer can have low magnetization and thus poor spin filtering, and the interface layer is said to provide spin filtering.

[0004] MRAM constructs are needed, which are manufacturable and which have enhanced

20 magnetoresistance, that is, which enhance the signal difference between the 0 and 1 states of the cell.

SUMMARY

[0005] According to the invention, enhanced magnetoresistance (tunneling magnetoresistance (TMR) in a MTJ cell structure; giant magnetoresistance (GMR) in a GMR

25 cell structure) is provided by interposing a spin filtering element in the circuit in front of the MRAM cell structure, and connecting the spin filtering element with the MRAM structure by a spin hold element. A spin filtering element may serve several MRAM cell structures, by connecting the spin filtering element to a series of MRAM cell structures by a spin hold wire. Or, a spin filtering element and the spin hold element may be formed as adjacent layers in

30 each MRAM cell stack.

[0006] In one general aspect the invention features a MRAM construct including a MRAM (GMR or MTJ) cell structure having at least two ferromagnetic layers separated by a conductor layer (GMR) or an insulator layer (MTJ), and including a spin hold layer adjacent a first one of the two ferromagnetic layers, and a spin filtering layer adjacent the spin hold layer.

35 [0007] In another general aspect the invention features a MRAM array made up of a plurality such MRAM structures.

[0008] In some embodiments the spin filtering element includes a ferromagnetic material having a high magnetic polarization value, including for example a Mn-based CMR material such as, for example, $La_xSr_{1-x}MnO_3$ or $Pr_xCa_{1-x}MnO_3$, or a Mn-based ferromagnetic material such as, for example, NiMnSb, or other material such as, for example, Fe_3O_4, CrO_2.

[0009] In some embodiments the spin hold element (layer or wire) is Bi. In other embodiments, where the spin hold element and the spin filtering element are adjacent layers in the MRAM stack, the spin hold layer can be a thin layer of a conductive metal, in which the thickness of the spin hold layer is less than the electron mean free path in the metal. Such embodiments include, for example, a layer of Cu having a thickness in the range about 4 nm to about 10 nm, or a layer of Al having a thickness in the range about 4 nm to about 5 nm.

[0010] In some embodiments the MRAM cell structure includes a MTJ system having two ferromagnet layers separated by a thin insulator, such as Al_2O_3. The ferromagnet layers have different coercivity fields; in some embodiments the MRAM cell structure includes a spin-valve MTJ, having for example a free ferromagnetic layer and a ferromagnetic layer pinned by a pinning layer such as an antiferromagnetic (AFM) layer, such as IrMn, or FeMn or CoFe/Ru/CoFe; in other embodiments the MRAM cell structure includes a "pseudo-spin-valve MTJ", having for example a soft ferromagnet layer and a hard ferromagnet layer. Here, "soft" and "hard" ferromagnets have coercivity fields respectively smaller (soft ferromagnet) and larger (hard ferromagnet). For example, where CoFe with a coercivity field of 50 Oe is selected as the hard ferromagnet material, then the soft ferromagnet material can be one that has a coercivity field smaller than 50 Oe, such as, for example, NiFe (having a coercivity about 10 Oe) or Co (having a coercivity about 30 Oe) or NiFeCo (having a coercivity about 20 Oe).

[0011] In some embodiments the MRAM cell structure includes a granular TMR system having a granular ferromagnetic material. Suitable granular TMR systems have many ferromagnetic grains embedded in an insulating matrix; such granular systems include, for example, $Fe-Al_2O_3$, $Fe-SiO_2$, or $Co-SiO_2$. The grain size and the inter-distance between ferromagnetic grains is in the range about 100 Å to about 300 Å.

[0012] In some embodiments the MRAM cell structure includes a GMR system having at least two (first and second) ferromagnetic layers separated by a thin conducting layer such as Cu, Ag, or Ru. The ferromagnet layers have different coercivity fields; in some embodiments the MRAM cell structure includes a spin-valve GMR, having for example a free ferromagnetic layer and a ferromagnetic layer pinned by a pinning layer such as an antiferromagnetic (AFM) layer, for example IrMn or FeMn or CoFe/Ru/CoFe; in other embodiments the MRAM cell structure includes a "pseudo-spin-valve GMR", having for example a soft ferromagnet layer and a hard ferromagnet layer. Here, "soft" and "hard" ferromagnets have coercivity fields respectively smaller (soft ferromagnet) and larger (hard ferromagnet). For example, where

CoFe with a coercivity field of 50 Oe is selected as the hard ferromagnet material, then the soft ferromagnet material can be one that has a coercivity field smaller than 50 Oe, such as, for example, NiFe (having a coercivity about 10 Oe) or Co (having a coercivity about 30 Oe) or NiFeCo (having a coercivity about 20 Oe).

[0013] In some embodiments the MRAM cell structure includes a GMR multilayer system having periodic ferromagnetic metal / nonferromagnetic metal layer, with several such periods, such as, for example, n periods of NiFe/Cu multilayer, that is, $(NiFe/Cu)_n$, and the like.

[0014] In some embodiments the MRAM cell structure includes a granular GMR system having a granular ferromagnetic material. Suitable granular TMR systems have many ferromagnetic grains embedded in a nonmagnetic insulating matrix; such granular structures include, for example, $Fe-Al_2O_3$, $Fe-SiO_2$, or $Co-SiO_2$. The grain size and the inter-distance between ferromagnetic grains is in the range about 100 Å to about 300 Å.

[0015] In another general aspect the invention features a MRAM construct including a plurality of MRAM (GMR or MTJ) cell structures each having at least two ferromagnetic layers separated by a conductor layer (GMR) or an insulator layer (MTJ), and including a spin filtering element connected to the several MRAM cell structures by a spin hold line adjacent a first one of the two ferromagnetic layers on the MRAM cell structures.

[0016] In another general aspect the invention features a MRAM array made up of such connected MRAM structures.

[0017] The invention provides for a TMR ratio that can exceed 100 % in MTJ structures having no defect, or having low defect; and the invention provides TMR ratios in MTJ that are higher than without the spin filtering element. The invention also provides for an enhanced GMR ratio in GMR structures.

[0018] In another general aspect the invention features a method for making a MRAM construct having a plurality of MRAM (GMR or MTJ) cell structures connected to a spin filtering element by a spin hold element. In some embodiments, in which forming the spin filtering element requires a high temperature anneal, the spin filtering element is formed prior to forming the MRAM cell structure, so that the high temperature anneal cannot adversely affect the MRAM cell structure. In other embodiments in which forming the spin filtering element requires a high temperature anneal, the high temperature anneal is carried out using pulsed laser energy, in which the pulse lengths and energy fluence are selected so that features adjacent the spin filtering element are not heated excessively during the anneal; in these embodiments the spin filtering element may be formed either prior to or following formation of the MRAM cell structure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] FIG. 1 is a diagram illustrating a first aspect of the invention.

[0020] FIG. 2 is a diagram illustrating a part of a memory array, according to an aspect of the invention, made up of elements as diagrammed in FIG. 1.

[0021] FIG. 3 is a diagram illustrating an aspect of the invention, as in FIG. 1, in further detail.

[0022] FIGS. 4A, 4B are diagrams illustrating spin configuration of a magnetic tunnel junction device with a spin filtering device according to an aspect of the invention, in the parallel state (FIG. 4A) and in the antiparallel state (FIG. 4B).

[0023] FIGS. 5A, 5B, 5C, 5D are diagrams illustrating spin states of a giant magnetoresistance device: without a spin filtering element, in the parallel state (FIG. 5A) and in the antiparallel state (FIG. 5C); and with a spin filtering element according to a second aspect of the invention, in the parallel state (FIG. 5B) and in the antiparallel state (FIG. 5D).

[0024] FIGS. 6A, 6B are diagrammatic sketches in sectional view showing the structure of a giant magnetoresistance (pseudo spin-valve structure) device with a spin filtering element according to an aspect of the invention.

[0025] FIGS. 7A, 7B are diagrammatic sketches in sectional view showing the structure of a giant magnetoresistance (spin valve structure) device with a spin filtering element as in FIGS. 6A, 6B, with additional pinning layer according to another aspect of the invention.

[0026] FIG. 8 is a diagrammatic sketch in an orthogonal view showing a portion of a memory array as in FIG. 2 according to an aspect of the invention.

[0027] FIG. 9 is a diagrammatic sketch in an orthogonal view showing a portion of a magnetic data storage array as in FIG. 6A according to an aspect of the invention.

[0028] FIG. 10 is a temperature-time plot illustrating a temperature regime during part of a process for forming a spin filtering element according to an aspect of the invention.

[0029] FIGS. 11A, 11B are flow diagrams showing steps in making a MRAM array according to further aspects of the invention.

DETAILED DESCRIPTION

[0030] The invention will now be described in further detail by reference to the drawings, which illustrate alternative embodiments of the invention. The drawings are diagrammatic, showing features of the invention and their relation to other features and structures, and are not made to scale. For improved clarity of presentation, in the FIGS. illustrating embodiments of the invention, elements corresponding to elements shown in other drawings are not all particularly renumbered, although they are all readily identifiable in all the FIGS.

[0031] Turning now to the drawings, FIG. 1 illustrates diagrammatically the general arrangement of parts in a device according to a first aspect of the invention. Particularly, a spin filter 12 is in this aspect connected by way of a spin hold wire 14 to a magnetic random access memory (MRAM) cell 16.

[0032]   The spin filter **12** is formed of a conductive ferromagnetic material having a high magnetic polarization value (P) and, accordingly it may be formed of materials that have magnetic polarization values that are high (P > 50 %) and ultra-high (P ~ 90 %). These materials include transition materials having high magnetic polarization values, such as for example Co_xFe_{1-x} alloys (P ~ 55 %) or $Co_xFe_{1-x}B_y$ alloys (P ~ 60 %), and semi-metallic ferromagnetic materials (or Heusler alloys) having ultra-high magnetic polarization values (P > 90 %), such as Fe_3O_4, CrO_2 or $La_xSr_{1-x}MnO_3$ (LMSO) or $Pr_xCa_{1-x}MnO_3$ or NiMnSb. The magnetization of these spin filter materials must be parallel or antiparallel t that of the reference layer of the MTJ or GMR cell in order to degrade the destruction of electron polarization from misaligned magnetization. Because these spin filter materials have magnetic properties similar to the MRAM cell, except for the spin polarization (P) value, the scalability is similar to that of the MRAM cell. For the in-plane magnetization design (the traditional MRAM design) the scalability can reach in the order of several times 10 nm. For the out-of-plane design (perpendicular magnetization of the MRAM cell), the scalability can reach in the order of several nm. The current flow in the spin filter material cannot affect the performance of the spin filtering, due to the definition of magnetization alignment between the spin filter material and the MRAM cell.

[0033]   Other suitable materials for the spin filter include: manganese-based GMR materials such as, for example, NiMnGa or NiMnSb; manganese-based ferromagnetic materials such as, for example, $La_xSr_{1-x}MnO_3$ or $Pr_xCa_{1-x}MnO_3$; or other materials such as, for example, Fe_3O_4 or CrO_2.

[0034]   MRAM cell **16** includes a magnetic tunnel junction (MTJ) structure. The spin hold wire or spacer is constructed of a material that has a long spin diffusion length, such as bismuth, which may be in a single-crystal form (monocrystalline Bi) or a poly-crystal form (polycrystalline Bi).

[0035]   Employing the spin filtering element significantly improves the tunneling magnetoresistance in the MTJ cell. The extent of the improvement can be identified, with reference to FIGS. **4A**, **4B**, as follows. FIG. **4A** diagrammatically illustrates the spin states of the spin filter **41**, and the first ferromagnet **42** and the second ferromagnet **43** of the TMR device where the MTJ is in a parallel magnetic state; and FIG. **4B** diagrammatically illustrates the spin states of the spin filter **41**, and the first ferromagnet **42** and the second ferromagnet **44** of the TMR device where the MTJ is in an antiparallel magnetic state.

[0036]   Let the polarization values of the spin-filtering element, the first ferromagnet, and the second ferromagnet be P_1, P_2, and P_3, respectively. If the MTJ is in the parallel magnetic state (FIG. **4A**), the tunneling current I_P with spin-conservation is:

$$I_P \propto \left(1+p_1\right)\left(1+p_2\right)\left(1+p_3\right)+\left(1-p_1\right)\left(1-p_2\right)\left(1-p_3\right).$$

[0037] If the MTJ is in the antiparallel magnetic state (FIG. **4B**), the spin configuration of the majority or minority band of the second ferromagnet **44** is opposite that of the first ferromagnet **42**. Here the ideal tunneling current I_{AP} with spin-conservation is:

$$I_{AP} \propto (1 + p_1)(1 + p_2)(1 - p_3) + (1 - p_1)(1 - p_2)(1 + p_3).$$

[0038] The tunneling magnetoresistance *TMR* is:

$$TMR = \frac{2(p_1 p_3 + p_2 p_3)}{1 + p_1 p_2 - p_1 p_3 - p_2 p_3} \times 100\%.$$

[0039] For example, where the magnetic polarization values of the first and second ferromagnets are P_2 = 50 % and P_3 = 50 %, the TMR ratio is 66 % without the use of a spin filter. If, on the other hand, a spin filter is employed according to the invention, and if the spin filter is formed of CrO_2 (P_1 = 90 %), the maximum TMR ratio can reach 187 %, which is much larger than that without spin filter. Here, the values of P_1, P_2, and P_3 are higher; the TMR ratio of MTJ is higher.

[0040] In practice, there may be defects at the MTJ interfaces, introducing scattering. To account for defects, a scattering factor f may be introduced into the equations for I_P and I_{AP}. The parallel state tunneling current with inelastic tunneling is expressed as:

$$I_P \propto [(1 + p_1)(1 + p_2)(1 + p_3) + (1 - p_1)(1 - p_2)(1 - p_3)](1 - f) + \\ [(1 + p_1)(1 + p_2)(1 - p_3) + (1 - p_1)(1 - p_2)(1 + p_3)](f) \quad ;$$

[0041] and the antiparallel state tunneling current with inelastic tunneling is expressed as:.

$$I_P \propto [(1 + p_1)(1 + p_2)(1 + p_3) + (1 - p_1)(1 - p_2)(1 - p_3)](1 - f) + \\ [(1 + p_1)(1 + p_2)(1 - p_3) + (1 - p_1)(1 - p_2)(1 + p_3)](f)$$

[0042] The TMR ratio for the MTJ having defects at the interfaces is:

$$TMR = \frac{(1 - 2f)(p_1 p_3 + p_2 p_3)}{1 + (p_1 p_2 - p_1 p_3 - p_2 p_3) + 2 f p_1 p_3 + 2 f p_2 p_3} \times 100\%.$$

[0043] For example, assuming a large spin-flip scattering factor f = 0.3 (TMR = 0 for f = 0.5), the TMR ratio without a spin filter is 11 %. If, on the other hand, a spin filter is employed according to the invention, and if the spin filter is formed of CrO_2 (P_1 = 90 %), the maximum TMR ratio can reach 24 %, which, while much lower than the ideal case, is significantly larger than that without the spin filter.

[0044] The spin filter is constructed *in situ*, and certain steps of the process for forming the preferred spin filter materials may be incompatible with at least some elements of the MRAM cell. That is, if parts of the MRAM cell are formed before the spin filter, then the MRAM parts must be protected during spin filter construction.

[0045] Referring now to FIG. **2**, there is shown a diagram illustrating a part of a memory array, according to an aspect of the invention, made up of elements as diagrammed in FIG. **1**. The

figure excludes the program circuits. Particularly, the array includes rows **21, 22', 22"** of magnetic tunnel junction (MTJ) cells **26** connected by way of a spin hold wire **24** to spin filters **22**. The length **23** of spin wire segments between nearest spin filters is determined by the spin-diffusion length of the spin wire, which can reach several μm or more, depending upon its crystalline structure, and the spin hold wire **24** can support several MTJ cells **26** on one segment, having a length **23**, in a given row. The fabrication of the spin-filtering element and spin-hold wire can be done before or after the fabrication of MRAM cell.

[0046] The operation of the spin filter is illustrated diagrammatically in FIG. **3**. The initial electron current in the wire **31** before the current is introduced into the spin filtering element **32** includes spin up **37** and spin down currents **39** are equivalent; that is, there are the same number of spin up electrons as spin down electrons in the initial current. As the current flows through the spin-filtering element, a significant proportion of the spin down electrons can be filtered out. As a result, as the current enters the spin hold wire **34** there is a much greater proportion of spin up electrons **37'** than spin down electrons **39'**. Hence, the electron spin configuration in the spin hold wire is predominantly (almost exclusively) spin-up. The filtered current is tapped from the spin hold wire and introduced into the MRAM cell **36**. Over the length of the spin hold wire, the spin configuration diffuses progressively, so that at some point along the spin hold wire it will be necessary to pass the current through a subsequent spin filter, as illustrated in FIG. **2**.

[0047] The MRAM cell **36** is a conventional cell; it includes a first ferromagnetic layer **362** and a second ferromagnetic layer **368** separated by a separation layer **364**. Where the MRAM cell is a MTJ, the separation layer **364** can be an insulator layer; where the MRAM cell is a GMR cell, the separation layer **364** can be a thin conductive layer. The first ferromagnetic layer and the second ferromagnetic layer can be formed of a 3d transition ferromagnetic metal such as, for example, Fe, Co, NiFe, CoFe, FeCoNi; or an alloy (or a Heusler alloy) such as, for example, Fe_3O_4, CrO_2, $La_xSr_{1-x}MnO_3$, $Pr_xCa_{1-x}MnO_3$; the insulator layer of the MTJ can be formed of, for example, Al_2O_3, AlN, AlON, Ga_2O_3, $SrTiO_3$ (STO), HfO_2, Ta_2O_5, and the conductor layer of the GMR can be formed of, for example, Cu, Ag, Au, Ru, Cr.

[0048] FIGS. **5A, 5B, 5C, 5D** are diagrams illustrating spin states of a giant magnetoresistance device: without a spin filtering element, in the parallel state (FIG. **5A**) and in the antiparallel state (FIG. **5C**); and with a spin filtering element according to a second aspect of the invention, in the parallel state (FIG. **5B**) and in the antiparallel state (FIG. **5D**). Each giant magnetoresistance (GMR) device is a layered structure includes a first ferromagnet layer **562** and a second ferromagnet layer **568**, separated by a conductor layer **564**. In these FIGS., spin-up electrons are symbolically represented in boxes **57, 57'**, and spin-down electrons are symbolically represented in boxes **59, 59'**. According to the invention, the electron current is passed through the spin filter before it goes into the GMR

device. As a result, the proportion of electrons that are spin-up is greater according to the invention, as shown in FIGS. **5B, 5D**, than it is without the use of a spin filter, as shown in FIGS. **5A, 5C**. When the GMR device is in the anti-parallel state, as shown in FIGS. **5C, 5D**, spin-dependent scattering of all the electrons is 100 %, or nearly so. When the GMR device is in the parallel state as shown in FIGS. **5A, 5B**, spin-dependent scattering of the spin-down electrons is 100 %, or nearly so; whereas spin-dependent scattering of the spin-up electrons is zero, or nearly so. The GMR ratio is enhanced according to the invention because the proportion of spin-up electrons in the current entering the GMR device is greater.

[0049] Considering the entire spin-dependent scattering in the GMR device to be $\rho\uparrow\uparrow = 0$, and $\rho\downarrow\downarrow = \infty$; **R**$\uparrow\uparrow$ according to the invention is less than **R**$\uparrow\uparrow$ where no spin-filtering element is employed; and **R**$\uparrow\downarrow$ according to the invention is less than **R**$\uparrow\downarrow$ where no spin-filtering element is employed. The GMR ratio is expressed as:

$$GMR = \frac{R\uparrow\downarrow - R\uparrow\uparrow}{R\uparrow\uparrow} \times 100\% .$$

[0050] Accordingly, an enhanced GMR ratio is provided according to the invention.

[0051] The structures of two alternative embodiments of a GMR or MTJ MRAM cell with a spin filtering element according to an aspect of the invention are shown in a diagrammatic sectional view in FIGS. **6A, 6B**. The GMR or MTJ structure **61** includes first and second ferromagnet layers **62, 68**, separated by (respectively) conductor or insulator layer **64**. A spin-hold layer **69** is adjacent the first ferromagnet layer **62**, and the spin filtering element **67** is adjacent the spin-hold layer **69**. Metal line **63** is adjacent the second ferromagnet layer **68** of the GMR structure **61**; and metal line **65** is adjacent the spin filtering element **67**. In FIG. **6A**, the spin filtering element is formed before the GMR structure, while in FIG. **6B**, the spin filtering element is formed after (over) the GMR or MTJ structure. Where the material of the spin filtering element includes a high temperature processing step, the spin-filtering element is formed before the GMR or MTJ structure, to avoid inter-diffusion with the GMR multilayer or the MTJ during processing. Or, where it is necessary to form a high temperature spin filtering element over a GMR or MTJ structure, a laser anneal may be employed to form the spin filtering element, as described below. On the other hand, where the material of the spin-filtering structure does not include a high temperature processing step, as for example at low temperature or room temperature, the GMR or MTJ may be formed either before or after the spin filtering element.

[0052] A pinning layer may be formed adjacent the spin filtering element in the GMR or MTJ MRAM cell with a spin filtering element as shown in a diagrammatic sectional view in FIGS. **7A, 7B**. The GMR or MTJ structure **61** includes a first and second ferromagnet layers **62, 68**, separated by insulator or conductor layer **64**. A spin-hold layer **69** is adjacent

the first ferromagnet layer **62**, and the spin filtering element **67** is adjacent the spin-hold layer **69**. Adjacent the spin filtering element **67** is the pinning layer **66**, which may be a permanent magnetic material or an antiferromagnetic (AFM) material. In FIG. **7A**, the spin filtering element is formed before the GMR or MTJ structure, while in FIG. **7B**, the spin filtering

5   element is formed after (over) the GMR or MTJ structure. As noted with reference to FIGS. **6A**, **6B**, the spin-filtering element must be formed before the GMR or MTJ structure, to avoid inter-diffusion with the multilayer of the GMR or MTJ during processing, if the material of the spin filtering element includes high temperature processing step. Or, where it is necessary to form a high temperature spin filtering element over a GMR or MTJ structure, a laser anneal

10   may be employed to form the spin filtering element, as described below. On the other hand, where the material of the spin-filtering structure does not include a high temperature processing step, as for example at low temperature or room temperature, the GMR or MTJ may be formed either before or after the spin filtering element.

[0053] Suitable materials for the GMR or MTJ structure **61** include two ferromagnetic layers

15   separated by a conductor layer (GMR) or by an insulator layer (MTJ). Suitable materials for the ferromagnetic layers include, for example, 3d transition ferromagnetic metals such as, for example, Fe, Co, NiFe, CoFe, FeCoNi; or an alloy (or a Heusler alloy) such as, for example, Fe_3O_4, CrO_2, $La_xSr_{1-x}MnO_3$, $Pr_xCa_{1-x}MnO_3$. The insulator layer of the MTJ can be formed of, for example, Al_2O_3, AlN, AlON, Ga_2O_3, $SrTiO_3$ (STO), HfO_2, Ta_2O_5; and the conductor layer of the

20   GMR can be formed of, for example, Cu, Ag, Au, Ru, Cr. Suitable materials for the spin filtering layer **67** include, for example, an alloy (or a Heusler alloy) such as, for example, Fe_3O_4, CrO_2, NiMnSb, NiMnGa, $La_xSr_{1-x}MnO_3$, $Pr_xCa_{1-x}MnO_3$. Suitable materials for the spin hold layer **69** include single-crystal or poly-crystal Bi. Suitable materials for the pinning layer **66** include permanent magnetic materials such as, for example, SmCo or SmFeCo; and

25   antiferromagnetic materials such as IrMn, FeMn, or CoFe/Ru/CoFe synthetic antiferromagnetic multilayer or IrMn/CoFe/Ru/CoFe multilayer structures.

[0054] A three-dimensional view of an embodiment of the invention as diagrammed in FIG. **2** and FIG. **3** is shown generally at **80** in FIG. **8**. In this illustrative example, a spin filtering element **32** is connected by way of a spin hold wire **34** to a series of three MRAM cells, in one

30   of many parallel rows in the MRAM array. Each MRAM cell **81** includes a MTJ or GMR system **36**. A current flows in a metal line **31** to the spin filtering element **32**, which filters out most of the spin-down electrons. The filtered electron current flows from the spin filtering element through the spin hold wire **34** to the GMR or MTJ systems **36** in the series. Metal lines **86** connect the MRAM cells **81** to MRAM cells in other series in the MRAM array by the

35   metallic platform **84**. Metal lines **83** and **81** support current to produce magnetic field to write to the MRAM cell when the write operation is started. As will be appreciated, the spin hold

wire can extend over a large number of MRAM cells in series, and can be provided at intervals with additional spin filtering elements, as shown for example in FIG. 2.

[0055] A three-dimensional view of an embodiment of the invention as diagrammed in FIG. 6A is shown generally at 90 in FIG. 9. In this illustrative example, a portion (including nine MRAM cells) of an MRAM array are shown. The transistor 92 serves as a selective device of the MRAM array. The metal lines 94 connect the gate of transistor 92 to control the turn-on or turn-off state. A connecting via connects the drain side of the transistor and the bottom layer of the stacked MRAM cell. Each MRAM cell 91 includes a MTJ or GMR system 61. Adjacent each MTJ or GMR system 61 is a spin hold layer 69, and adjacent each spin hold layer 69 is a spin filtering element 67. A current is supplied from the periphery to the selective transistor 92. This current is flowed through contact and via and is introduced into the spin filter 67 of a series of MRAM cells. The spin filtering layers 67 filter out most of the spin-down electrons. In each MRAM cell the filtered electron current flows through the spin hold layer 67 to the MTJ or GMR system 61. Metal lines 63 connect the MRAM cells 61 to MRAM cells in other series in the MRAM array. For a write operation, the metal lines 91 and 65 supply currents to produce a magnetic field on the MRAM cell.

[0056] Steps in a process for manufacturing MRAM arrays according to the invention are shown in flow diagrams in FIGS. 11A and 11B.

[0057] The spin filter material is formed at a higher temperature than is employed in manufacture of the MRAM cell. In one process, shown in FIG. 11A, the spin filter is formed prior to formation of the MRAM cell. First, the spin filter material is deposited 111 using a deposition technique such as, for example, PVD, IMD, CVD, or MOCVD, and then the deposited material is further annealed 113 by furnace or RTP or by Laser annealing. The anneal temperature and anneal time is selected according to the crystallization point of the material. For example, if LSMO ($La_xSr_{1-x}MnO_3$) is employed as the spin filter material, an anneal is carried out at a temperature in the range about 300 °C to about 450 °C for time in the range about, for example, 1/2 day. After the annealing process, the material is patterned by photo etch 115. Then the MRAM cell is deposited and patterned 117.

[0058] In an alternative process, shown in FIG. 11B, the MRAM cell is formed prior to formation of the spin filter and, because the thermal stability of MRAM cell is weaker than that of the spin filter material, the temperature treatment of spin filter element must be carefully controlled to limit damage to the MRAM cell. Laser annealing is particularly suitable in this situation, because it provides very rapid thermal ramp-up and down. After the MRAM cell is formed and patterned 112, the spin filter material is deposited 114. Then the laser anneal is performed to anneal the spin filter material only 116. The annealed spin filter element is then patterned by photo etch 118.

[0059] A generalized temperature regime for the laser anneal, rapid thermal anneal (RTA), or furnace anneal step in forming the spin filtering element is shown graphically in FIG. 10. Laser energy pulses are fired onto the deposited spin filtering material, to ramp the temperature rapidly up, as shown at 102, from ambient (T_{amb}), which may be about room temperature, to

5   an annealing temperature 104 (T_{ann}). The laser firing is maintained for a time sufficient to effect the anneal, and then the laser is shut off, to allow the temperature to fall, as shown at 106, back to ambient. As will be appreciated, the pulse rate and pulse duration, and the energy fluency, will be selected to provide rapid localized heating of the spin filtering material to the required anneal temperature, without raising adjacent regions to temperatures that

10   would cause damage to nearby features (particularly, the MTJ or GMR) that have already been formed. The RTA and furnace anneal processes have a similar temperature regime, as shown in FIG. 10. The time scale for the RTA process is in the order of several seconds, and the time scale for the furnace anneal is in the order of several minutes to several hours. The time scale for the laser anneal is in the order of several μseconds.

15   [0060] Annealing temperature and anneal time are selected according to the melting point and the crystallization behavior of the particular material. Generally a suitable annealing temperature is given by (Tm + 273) / 2, where Tm is the melting point of the material in degrees Centigrade. Such an annealing temperature can result in formation of a single crystal. It may not be necessary, however, to obtain a single crystal; accordingly, a denominator

20   greater than 2 (for example, 3) can be used to determine an anneal temperature in a particular instance. For example, in a furnace anneal process, a satisfactory texture can be obtained in NiMnGa by annealing at 800 °C for an extended time (as long as 1 day, for example).
[0061] On the other hand, damage to an MTJ material can result at a temperature as little as 400 °C, and damage to a GMR material can result at a temperature as little as 300 °C, and so

25   it is important that parameters of the laser (e.g., wavelength, energy) be set so that adjacent features are not excessively heated. By way of example of a laser anneal process carried out following formation of the MTJ or GMR, a KrF excimer laser employed at 120 mJ can raise the temperature sufficiently to heat and anneal the spin filter material. Suitable shot durations may be in the order of about several μsec. The energy can be delivered at a rate about, for

30   example, 10 Hz, to protect the prior MTJ or GMR material from damage by heat.

[0062] Other embodiments are within the following claims.